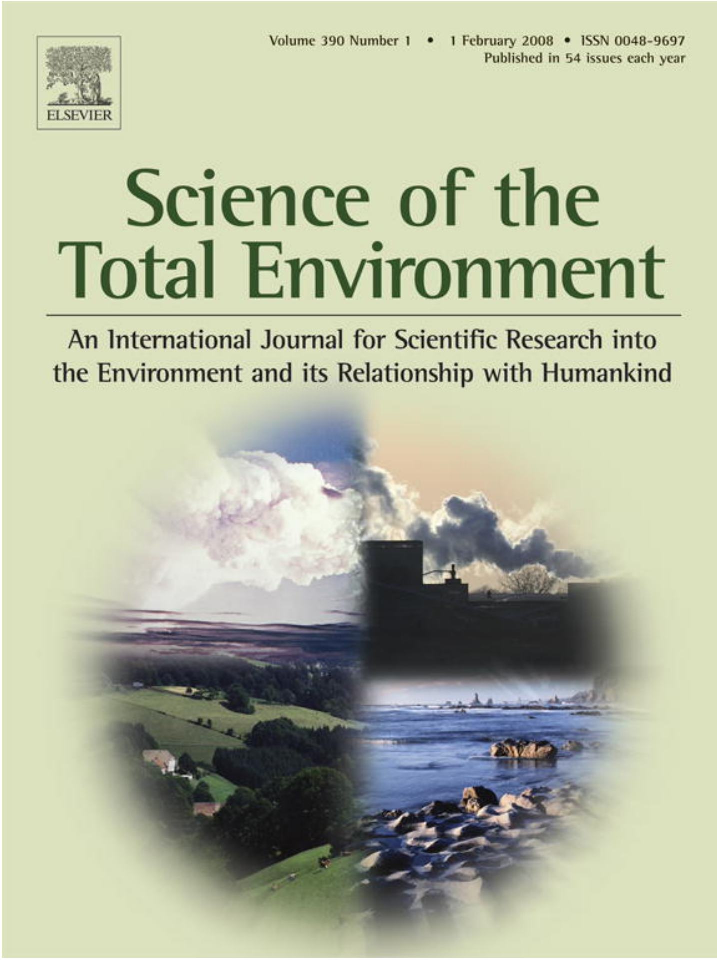
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Estuarine habitat quality reflects urbanization at large spatial scales in South Carolina's coastal zone

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ABSTRACT

Land cover patterns were evaluated in 29 estuarine watersheds of South Carolina to determine relationships between urban/suburban development and estuarine habitat quality. Principal components analysis and Pearson product moment correlation analyses were used to examine the relationships between ten land cover categories and selected measures of nutrient or bacterial enrichment in the water column and contaminant enrichment in sediments. These analyses indicated strong relationships between land cover categories representing upland development and a composite measure of 24 inorganic and organic contaminants using the Effect Range Median-Quotient (ERM-Q). Similar relationships also were observed for the summed concentrations of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and metals. Data obtained from tidal creeks generally showed stronger correlations between urban/suburban land use and pesticides and metals compared to data obtained from larger open water habitats. Correlations between PAH concentrations and the urban/suburban land cover categories were similar between creek and open water habitats. PCB concentrations generally showed very little relationship to any of the land cover categories. Measures of nutrient enrichment, which included total Kjeldahl nitrogen (TKN), nitrate–nitrite, phosphorus, chlorophyll-a, and total organic carbon, were generally not significantly correlated with any land cover categories, whereas fecal coliform bacteria were significantly and positively correlated with the urban/suburban land cover categories and negatively correlated with the non-urban land cover categories. Fecal coliform correlations were stronger using data from the open water sites than from the tidal creek sites. Both ERM-Q and fecal coliform concentrations were much greater and more pervasive in watersheds with relatively high (>50%) urban/suburban cover compared to watersheds with low (<30%) urban/suburban cover. These analyses support the hypotheses that estuarine habitat quality reflects upland development patterns at large spatial scales, and that upland urbanization can result in increased risk of biological degradation and reduced safe human use of South Carolina's coastal resources.

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1. Introduction

Development along most of the coastal zone of the United States is projected to increase from 80 million to 127 million people over the next 20 years (Zinn, 1997). In South Carolina alone, population growth in the coastal counties has been increasing rapidly, with more than 1.04 million people estimated to be living in the eight coastal counties in 2004 (SC Budget and Control Board, 2005). This number is expected to increase another 30% by 2025. The construction of infrastructure (e.g., roads, commercial development, residential housing, industry) that accompanies human development will alter the rate and volume of freshwater inflow as well as the type and amount of pollutants introduced into estuaries (Fulton et al., 1993; Mallin et al., 2000), with considerable potential for estuarine habitat degradation. Many other developed coastal states are already observing serious degradation of their coastal estuarine habitat, due largely to high contaminant and nutrient concentrations (Bricker et al., 1999; USEPA, 2004) and increased fecal coliform bacterial levels which impact the suitability of these estuaries for shellfish harvesting and primary contact recreation (Vernberg et al., 1996; Mallin et al., 2000; Kelsey et al., 2004; Nelson et al., 2005).

While changes in the quality of receiving water bodies in response to changes in land use associated with urbanization have been well documented for freshwater drainage systems (Schueler, 1994; Arnold and Gibbons, 1996; Schueler and Holland, 2000), similar studies are generally lacking in estuarine environments. Sanger et al. (1999a,b) and Holland et al. (2004) documented the effects of land use change on the quality of intertidal creek habitats that represent the headwaters of many estuarine drainage systems in South Carolina. Their studies indicated that when impervious cover exceeded 10–20% of the upland watershed, there were measurable alterations in the hydrography, salinity variance, sediment characteristics, contaminant levels, and fecal coliform loadings in these small creeks. When the amount of impervious surface exceeded 20–30%, living resources were affected as well. Because those studies were generally limited to the intertidal headwater portions of tidal creeks, it is unclear whether similar effects would be observed in larger subtidal creeks or more open estuarine water bodies such as South Carolina's tidal rivers, bays and sounds.

Other studies in South Carolina have examined alterations in estuarine habitat quality related to differences in land use patterns (e.g., Vernberg et al., 1992; Fulton et al., 1993), but these studies were limited to two relatively small watersheds in the state. Studies conducted in other states have documented degradation of estuarine habitats with elevated levels of urbanization and population density at larger spatial scales (Comeleo et al., 1996; Dauer et al., 2000; Paul et al., 2002; Nelson et al., 2005). However, many of these studies may not be applicable to South Carolina as they were conducted in estuaries that have much greater urban/suburban, industrial, and agricultural inputs, or they involved regions other than the southeast coast of the United States.

Within the southeast US, South Carolina and Georgia have unique coastal watershed characteristics compared to North Carolina and Florida due to relatively high tidal amplitudes (4.6–7.9 m; International Marine, 1995) and low coastal topography. Together, these characteristics result in extensive marshgrass-dominated wetlands and complex tidal creek systems that drain the upland areas. These tidal creeks support a diverse assemblage of estuarine fauna and serve as critical nursery habitat for many of those species. As a result, several monitoring programs have recently focused on evaluating the condition of both tidal creek and larger open water habitats (Van Dolah et al., 2000, 2002, 2003, 2004a,b, 2006). The combination of these studies provides a rich database to evaluate relationships between estuarine habitat quality and upland land use patterns in coastal watersheds. In this study, we seek to determine (1) whether significant relationships can be observed between upland land cover and estuarine habitat quality in watersheds of moderate size, and (2) if so, whether differences in these relationships can be observed between tidal creeks and larger water bodies.

2. Methods

We selected 29 US Geological Survey (USGS) 14-digit Hydrologic Unit Code (HUC) watershed boundaries for analysis of land use patterns (Fig. 1). The HUCs were selected to include the full range of watersheds that were characterized by different proportions of upland development and were limited to those that contained at least three sites that had been sampled for one or more of the estuarine water or sediment quality measures considered here.

Land cover characteristics were analyzed using Landsat Thematic Mapping Imagery obtained primarily in 1997/1998 by the USGS Earth Resources Observation Systems (EROS) Data Center. This imagery has a spatial resolution of 30×30 m and has been analyzed by the Land, Water and Conservation Division of the South Carolina Department of Natural Resources for land cover patterns (SCDNR, unpublished). Since a high percentage of the estuarine water and sediment quality data available for assessing the condition of South Carolina's estuaries were obtained from studies that had been conducted between 1993 and 2002, this Landsat imagery provided a useful assessment of existing land use patterns that corresponded to the same approximate time period when the environmental data were collected.

The imagery classifications compiled by the SCDNR include: open water; emergent wetlands; scrub/shrub wetlands; forested wetlands; scrub/shrub uplands; forested uplands (deciduous, evergreen and mixed); cultivated land; grassland/pasture; bare land; high intensity urban; and low intensity urban. Scrub/shrub wetland, scrub/shrub upland, and deciduous forest never comprised more than 4%, 8% and 4% of total upland cover, respectively, within any HUC and were therefore merged with the most ecologically similar land cover type to reduce the number of categories. These included merging scrub/shrub wetlands with forested wetlands, grassland/pasture with scrub/shrub upland, and deciduous forest with mixed forest upland. The low and high urban land use categories were analyzed both separately and combined. Low and high urban cover were defined by the SCDNR as having 30–75% and greater than 75% urban–suburban cover, respectively. The 29 HUCs were intersected with the land cover data within a GIS to obtain an estimate of the total area and

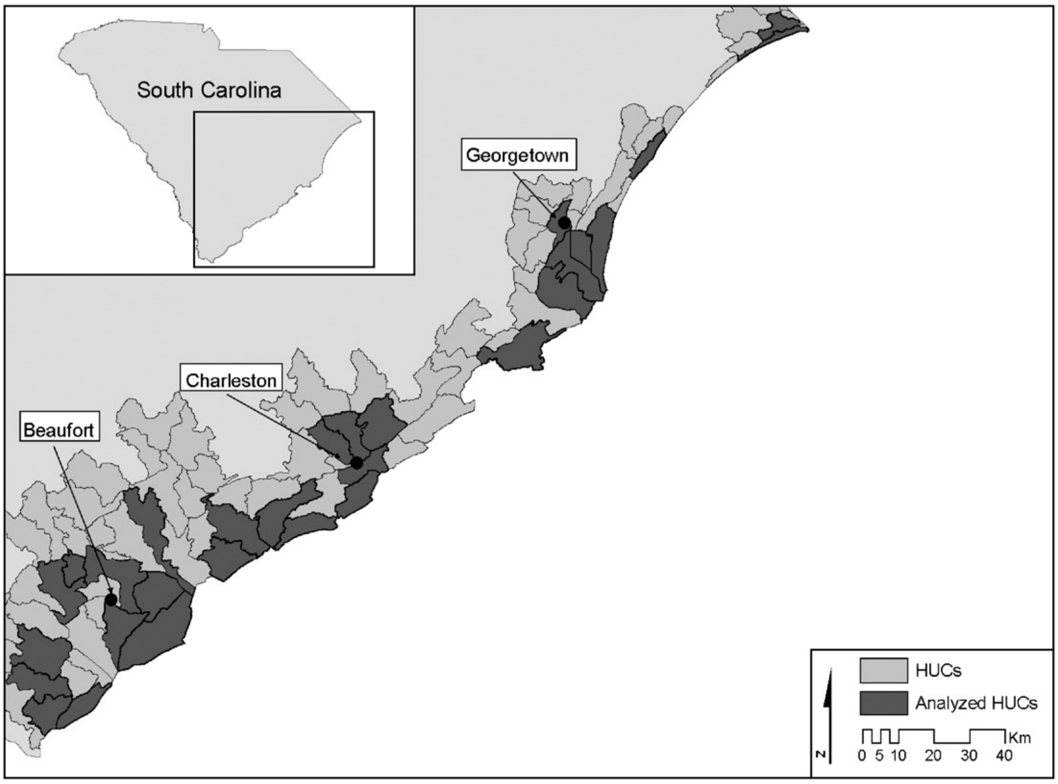

Fig. 1 – Location of the 29 14-digit Hydrologic Unit Code (HUC) watersheds selected for analysis.

percentage of upland habitat represented by each land cover category.

An analysis of the percent impervious cover within each watershed was obtained by applying a computer-generated triangular grid of points that was overlaid on high resolution color infrared National Aerial Photographic Program (NAPP) imagery taken during the winter of 1999. Each Digital Ortho Quarter Quad (DOQQ) was evaluated at a 1:12,000 scale scanned from a 1:40,000 NAPP image to provide 1-meter resolution. Points that fell on impervious surfaces were divided by the total number of points that fell on upland categories to estimate the percentage of upland as impervious surface. Depending on the size of the HUC, between 79 and 439 points (average of 198 points) were evaluated to compute percent impervious cover.

To evaluate estuarine habitat condition within each watershed, several studies that collected comparable data were collated into one database that included 617 stations within the 29 watersheds. The South Carolina Estuarine and Coastal Assessment Program provided most of the data that had been collected from 1999–2002 for most water and sediment quality parameters (Van Dolah et al., 2002, 2004a) with a total of 180 stations sampled. Four other studies that had been conducted within the 29 watersheds provided additional data using similar sampling protocols. They included an assessment of 12 subtidal stations in Broad Creek on Hilton Head Island and the Okatee River during 1997 (Van Dolah et al., 2000), 9 subtidal stations in the May River sampled during 2002 (Van Dolah et al., 2004b), 29 subtidal estuarine stations sampled throughout South Carolina from 1993–1995 as part of the Carolinian Province Environmental Monitoring and Assessment Program (Hyland et al., 1996, 1998; Ringwood et al., 1997), and 57 stations sampled in 1993 by Long et al. (1997) in the Charleston Harbor and Winyah Bay estuaries. Most of the data obtained from the latter three studies were limited to measures of sediment contaminants and sediment composition, and all of the studies were limited to a single sampling event at each site.

Two other major data sources used for this analysis were obtained from the South Carolina Department of Health and Environmental Control (SCDHEC). SCDHEC is responsible for regulating water quality in the state and therefore conducts monthly sampling throughout the state via their ambient surface water quality and shellfish monitoring programs. Data from 26 ambient surface water quality monitoring stations that were located within the selected watersheds were evaluated for fecal coliform and nutrient measures. An additional 304 stations in SCDHEC's shellfish monitoring program that were located within these watersheds were evaluated for fecal coliform bacterial concentrations only (STORET database). Because sampling for these programs was conducted monthly, all data collected for each parameter at a station during 1998 and 1999 were averaged for use in our analyses.

While some of these studies sampled a large suite of water or sediment quality variables, our primary interest was to evaluate relationships between land cover patterns in the watersheds and selected measures indicative of nutrient or bacterial enrichment in the water column, and contaminant enrichment in sediments. Based on the available data, the nutrient measures considered included total nitrate–nitrite (NO_2–NO_3; mg/L), total Kjeldahl nitrogen (TKN; mg/L), total phosphorous (Phos; mg/L), total organic carbon (TOC; mg/L), chlorophyll-a (Chlor-a; μg/L), and fecal coliform bacteria (Fecals; col./100 mL). All samples were processed by SCDHEC using standardized procedures (SCDHEC, 1998, 2001, 2005). Sites with concentrations below the detection limits for the above variables were treated as 0 values.

Sediment quality measures that were considered for this study included TOC (% of total sediment mass), silt/clay content (% of total), and a collective measure of sediment contaminant concentrations represented by an Effects Range Median-Quotient (ERM-Q, Long et al., 1995) using 24 contaminants as described by Hyland et al. (1999). The ERM-Q is calculated for each sediment sample by summing the ratios of each chemical concentration divided by the ERM value for that chemical (ERM = median concentration for which adverse effects were noted on a variety of benthic organisms), and then dividing that sum by 24 (the number of chemicals considered in this study). The 24 chemicals include 8 metals (arsenic, cadmium, chromium, copper, lead, mercury, silver, zinc), 13 polycyclic aromatic hydrocarbons (PAHs: acenaphthene, acenaphthylene, anthracene, benzo[*a*] anthracene, benzo[*a*]pyrene, chrysene, dibenz[*a*,*h*+*a*,*c*]anthracene, fluoranthene, fluorine, 2-methylnaphthalene, naphthalene, phenanthrene, pyrene), total polychorinated biphenyls (PCBs), and the pesticides 4,4′DDE, and total DDT. Using these same 24 chemicals, we also computed the sum total concentration of metals (ppm), PAHs (ppb), PCBs (ppb), and pesticides (ppb). Analytical procedures for each of these parameters are referenced by Hyland et al. (1999) and Van Dolah et al. (2002).

The data for each water and sediment quality parameter were averaged from all stations sampled within each watershed for statistical comparison with land cover patterns. Within each HUC, averages were computed using only tidal creek stations, only open water stations, and all stations combined. Tidal creeks were defined as any estuarine water body narrower than 100 m from marsh bank to marsh bank. Only those HUCs represented by at least three stations in the overall estuarine dataset or in each habitat type (tidal creek or open water) were included in the analyses.

Statistical analyses of land use and environmental variables were performed using Minitab 12 and Sigmastat 3.1. Prior to analysis, all environmental variables were transformed, when necessary, to ensure the data were normally distributed. Principal components analysis (PCA) was used first to examine overall structure in the environmental data matrix for open water and tidal creek habitats combined. Only 25 of the 29 HUCs had data available on all parameters, so these were the only ones used in this analysis. To investigate relationships between overall environmental data structure and land use cover, the Pearson product moment correlation (Pearson's *r*) was used to correlate the scores for each HUC on the first two principal components with the percentage of upland areas that were represented by the various land cover categories in those HUCs. Pearson's *r* matrices were then generated to further analyze specific relationships between the individual environmental variables and land cover patterns (percentage of total upland area). When a normal distribution could not be achieved, a Spearman rank correlation was substituted for the Pearson's *r* analysis.

3. Results

3.1. *Land cover and data array patterns*

The 29 watersheds ranged in total size from 3,006 to 22,674 ha, but only one watershed had more than 16,000 ha. The percentage of upland habitat in each watershed represented by urban cover (low and high urban combined) ranged from 0 to 78% (Fig. 2). Thirteen watersheds had less than 10% urban cover, eight watersheds had between 10 and 30% urban cover,

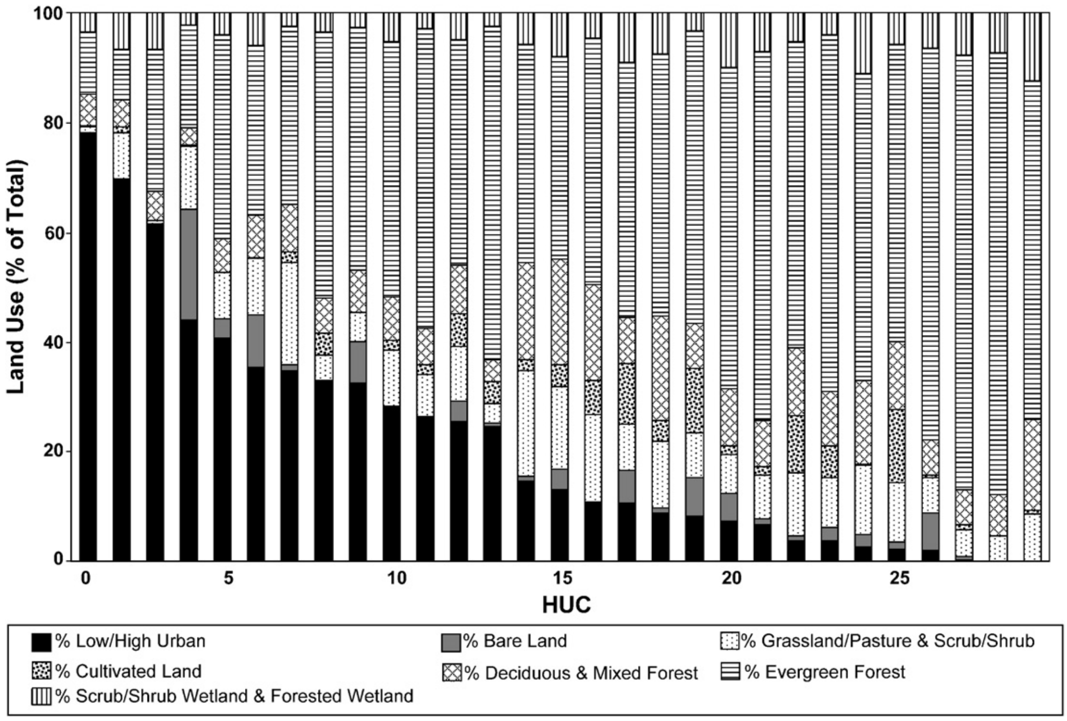

Fig. 2 – Proportion of the various land cover categories used to characterize the upland watershed.

and the remaining nine watersheds had greater than 30% urban cover. Bare land was generally less than 10% of the upland cover except in one watershed. Cultivated land ranged from 0 to 13% of the upland cover, but only four watersheds had more than 10% cultivated land cover. Evergreen forests were the most common form of undeveloped land, ranging from 9 to 80% of total land cover (Fig. 2).

When both tidal creek and open water stations were combined, an average of 6.8–17.9 stations were sampled in each HUC depending on the variable considered (Table 1). Fecal coliform bacteria samples provided the highest average number of sites per HUC (17.9), followed by the contaminant variables (10.1) and other water quality variables (6.8–7.8). All 29 of the HUCs had at least three stations sampled for fecal coliform bacteria, and all but one HUC had three or more stations sampled for the sediment chemistry variables.

There was generally a higher number of open water stations than tidal creek stations within each watershed (Table 1). This is consistent with the relative areal extent of these two habitat types in South Carolina, and the fact that some of the historical databases considered did not target tidal creek habitat. The average number of stations representing each parameter ranged from 4.4–10.9 stations per HUC and the number of HUCs with sufficient data points (i.e.>3 stations) fell within the range of 16–29 for the open water analyses and 12–20 for the tidal creek analyses.

3.2. *Overall structure of environmental data matrix*

The Principal Components Analysis of the 25 HUCs that had data for all the environmental variables resulted in the first principal component accounting for 45.9% of the variability and the second component accounting for 15.7% of the variability (cumulatively 66.6%). The first principal component was a positive function (increase from left to right) of all the environmental characteristics measured (Fig. 3). However, sediment characteristics (silt/clay content and TOC-sediment), contaminants (Total PAH, PCB, Pesticides and Metals), and ERM-Q contributed most to this component (Table 2). The second component was a positive function of the sediment contaminants (of which only Total PCB's contributed substantially) and a negative function of all other environmental factors (of which NO_2–NO_3, Phos, TOC–water and fecals contributed most, Table 2).

The first principal component was correlated with an urbanization gradient, with low- and high-density urban development and impervious cover increasing in the positive direction and all other non-urban land uses increasing in the negative direction (Table 3, Fig. 3). These correlations were significant for the grassland/pasture, scrub/shrub, bare land, and urban high density, and marginally significant for deciduous and mixed forest, urban combined and impervious cover land cover categories. The second principal component was marginally significantly correlated with increasing evergreen forest cover (in the negative direction) and increasing high-density urban development (in the positive direction).

Several trends are apparent when the scores of each HUC were plotted on the first two principal components (Fig. 3). First, those HUCs with less than 50% urban cover tended to cluster at the left side of the plot (negative end of PC1). While several of these HUCs had rather high levels of low-density urban land cover, none had greater than 6% of high-density urban cover. In general, these HUCs were characterized by lower values of TOC, silt/clay, and contaminants. Second,

Table 1 – Total, mean and range of stations evaluated for the various sediment and water quality variables, and total number of HUCs represented for each variable

Sediment quality variables

	No. stations			Silt–clay			TOC			ERMQ			PAHs			PCBs			Pesticide			Metals		
	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O
Total number of stations	617	215	401	219	88	105	218	87	105	284	96	165	284	96	165	283	96	164	282	96	163	284	96	165
Mean number/HUC	21.3	8.6	13.8	7.8	5.2	5.0	7.8	5.1	5.0	10.1	5.1	7.9	10.1	5.1	7.9	10.1	5.1	7.8	10.1	5.1	7.8	10.1	5.1	7.9
Range	8–45	3–21	4–37	3–16	3–8	3–10	3–16	3–12	3–8	3–35	3–12	3–30	3–35	3–12	3–30	3–34	3–12	3–29	3–33	3–12	3–28	3–35	3–12	3–30
Total number of HUCS	29	25	29	28	17	21	28	17	21	28	19	21	28	19	21	28	19	21	28	19	21	28	19	21

Water quality variables

	No. stations			NO_2–NO_3			TKN			Phos			TOC			Chlor-a			Fecal coliform		
	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O	T	C	O
Total number of stations	617	212	401	184	60	96	194	66	104	189	63	100	199	73	101	189	81	74	519	195	315
Mean number/HUC	21.3	9.2	13.8	7.1	5.0	4.8	6.9	4.4	5.0	6.8	4.5	4.8	7.1	4.6	4.8	7.0	5.1	4.6	17.9	9.8	10.9
Range	8–45	3–20	4–37	3–14	3–11	3–9	3–14	3–10	3–11	3–15	3–12	3–11	3–14	3–9	3–9	3–15	3–12	3–8	6.43	3–20	3–22
Total number of HUCS	29	23	29	26	12	20	28	15	21	28	14	21	28	16	21	27	16	16	29	20	29

T = total, C = tidal creek, O = open water.

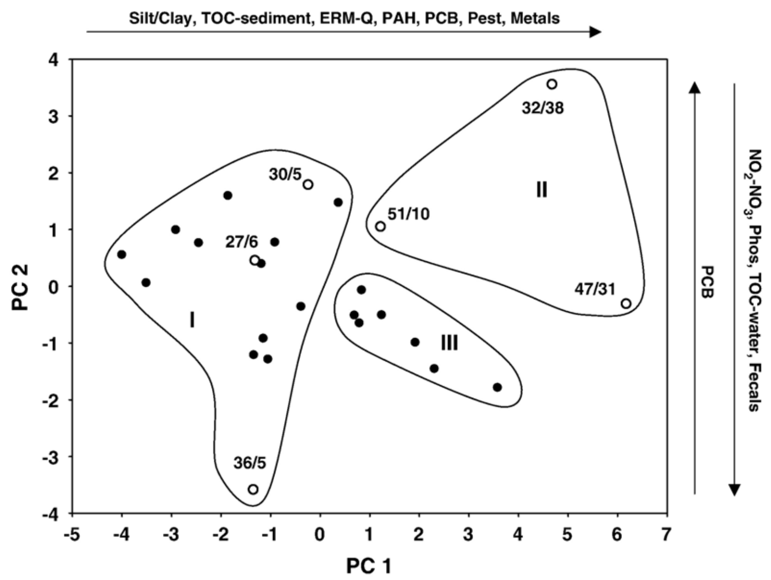

Fig. 3 – Plot of 14-digit HUC scores on the first two principal components derived from PCA. Closed circles = HUCs with less than 30% combined urban cover; open circles = HUCs with greater than 30% urban cover. Numbers beside open circles indicate amounts of low- and high-density urban land cover in those HUCs (low density/high density). I — HUCs with less than 50% combined urban land cover and low values for sediment characteristics and contaminants; II — HUCs with greater than 50% combined urban cover, III — HUCs with less than 10% urban cover but with high values for sediment characteristics and contaminants.

those HUCs with the greatest urban land cover, especially those with at least 10% high-density urban cover, clustered loosely at the upper right of the plot (positive on both PC1 and PC2) and tended to be characterized by higher values of TOC, silt/clay, and contaminants. A third cluster of practically non-urbanized HUCs (all with less than 10% combined urban cover) aligned in the lower right quadrant of the plot. These non-urbanized HUCs possessed sediment quality characteristics similar to the highly urbanized HUCs.

3.3. *Estuarine sediment quality and watershed land cover patterns*

Further analysis of the relationships between estuarine sediment quality variables and watershed land cover patterns using Pearson's r identified several consistent and significant relationships. When data from tidal creek and open water stations were combined, significant positive relationships were observed between mean ERM-Q concentration and high urban, combined urban, and percent impervious surface cover (Table 4), with the strongest relationship observed between ERM-Q and high urban cover ($p<0.01$). The only land cover category showing a significant negative relationship was bare land ($p<0.001$).

Similar and generally stronger correlations were observed when land cover categories were compared with ERM-Q measurements collected just from tidal creek habitats (Table 5). The tidal creek dataset showed significant correlations between ERM-Q and all four urban land cover categories, whereas only high urban cover showed a significant positive relationship with ERM-Q in the open water dataset.

When the contaminant sub-categories were considered separately, significant positive correlations were observed between PAH, PCB, and pesticide contaminant concentrations and the percentage of high urban, combined urban, and impervious surface cover when both tidal creek and open water data were combined. Significant negative correlations were observed for bare land and evergreen forest for several of these contaminants (Table 4). PAHs were also significantly negatively correlated with grassland, pasture and scrub/shrub land cover. Total metals concentration was only significant and positively correlated with high urban cover and negatively with bare land.

Comparison of these same contaminant categories using tidal creek and open water data separately showed some interesting differences (Table 5). For tidal creek stations, PAHs, pesticides, and metals were significant and positively

Table 2 – Coefficients of environmental variables for the first two principal components

Variable	PC1	PC2
NO_2–NO_3	0.181	−0.381
TKN	0.200	−0.019
Phos	0.115	−0.349
TOC–water	0.106	−0.525
Chlor-a	0.203	−0.115
Fecals	0.193	−0.422
Silt/clay	0.341	−0.067
TOC–sediment	0.365	−0.078
ERM-Q	0.386	0.162
PAHs	0.345	0.070
PCBs	0.311	0.372
Pest	0.266	0.251
Metals	0.373	0.149

Table 3 – Correlations between PCA based HUC scores and the land use percentages within those HUCs

Land cover category	PC1	PC2
Scrub shrub and forested wetlands	− 0.080	0.117
Bare land	**− 0.559**	0.023
Grassland/pasture and scrub/shrub	***− 0.449***	0.045
Deciduous and mixed forest	*− 0.350*	− 0.054
Evergreen forest	− 0.297	*− 0.396*
Cultivated land	− 0.182	0.102
Urban low density	0.207	0.196
Urban high density	**0.513**	*0.342*
Urban combined	*0.359*	0.274
Percent impervious surface	*0.369*	0.255

Boxes with bold coefficients represent $p<0.01$, boxes with bold italicized coefficients represent $p<0.05$ and boxes with italicized coefficients represent $p<0.10$.

correlated with all of the urban/suburban land cover categories. Although PCBs were not significantly correlated with these land cover categories, the correlations noted were positive. All contaminant types were significant and negatively correlated with bare land cover and both metals and PAHs were negatively correlated with other land categories. In contrast, the open water data set showed significant positive correlations between PAH and metal concentrations with all urban land cover categories (except low urban for metals only). PCBs and pesticides were more weakly correlated with some of the land cover categories. While correlations with the non-urban land cover categories were generally not significant, it is again notable that all of those categories were consistently negatively correlated with the various contaminant categories.

To examine the link between urban land use, sediment contamination and the potential for benthic community degradation, ERM-Q values of individual stations were assigned to low, moderate and high risk categories based on thresholds established by Hyland et al. (1999) (i.e. <0.020 low risk, >0.020 and <0.058 moderate risk, and >0.058 high risk of observing degraded benthic communities). For this analysis, watersheds were divided into those with relatively low urban/suburban cover (0–30% low and high urban/suburban cover combined), moderate urban/suburban cover (31–50%), and high urban/suburban cover (>50%). Approximately 77% of the sites sampled in the watersheds with >50% urban/suburban cover had elevated ERM-Q concentrations compared to only 27% of the sites sampled in watersheds with ≤30% urban/suburban cover (Fig. 4). The intermediate class of watersheds (31–50% urban/suburban cover) was similar to the group of HUCs with <30% urban/suburban cover.

3.4. *Watershed land cover patterns and estuarine water quality*

With the exception of fecal coliform bacteria, water quality parameters did not show strong correlations with urban land cover patterns (Tables 6 and 7). In all three data sets, fecal coliform bacterial concentrations were positively and significantly correlated with urban land cover measures and negatively correlated with all non-urban land cover categories (Tables 6 and 7). Correlation coefficients between fecal bacterial concentrations and land cover categories using only tidal creek stations were much weaker than observed for the combined data set (Table 7). In contrast, comparisons using only the open water data generally resulted in higher and more significant correlation coefficients, especially for several of the urban land cover categories. This was contrary to expectations since tidal creek habitats are in closer proximity to probable sources.

State water quality criteria require that no more than 10% of samples collected from a site can exceed 43 colonies/100 mL for “Shellfish Harvesting Waters” and no more than 10% of the samples should exceed 400 colonies/100 mL for primary contact recreation (SCDHEC, 2004). Comparison of the number of stations that exceeded these criteria in watersheds having lower combined urban cover versus higher combined urban cover provided a means to link the effects of upland urbanization with human estuarine

Table 4 – Pearson product moment correlation coefficients of comparisons between the different land cover categories and the sediment quality variables using all stations (tidal creek and open water) combined

Land cover category	Silt/clay[a]	TOC[a]	ERM–Q[a]	PAHs[a]	PCBs[a]	Pesticides[b]	Metals[a]
Non-urban							
Scrub/shrub and forested wetlands	0.206	0.069	0.087	− 0.006	− 0.066	− 0.216	0.152
Bare land	**− 0.552**	*− 0.368*	**− 0.591**	**− 0.591**	***− 0.421***	− 0.285	**− 0.506**
Grassland/pasture and scrub/shrub	− 0.263	**− 0.416**	− 0.257	*− 0.369*	− 0.265	− 0.179	− 0.237
Deciduous and mixed forest	0.061	− 0.282	− 0.171	− 0.162	− 0.265	− 0.209	− 0.222
Evergreen forest	0.011	− 0.026	− 0.300	*− 0.342*	*− 0.347*	*− 0.334*	− 0.218
Cutlivated land	− 0.101	− 0.133	− 0.069	− 0.234	− 0.029	− 0.099	− 0.075
Urban							
Urban low density	− 0.029	− 0.036	0.223	0.312	0.192	0.350	0.135
Urban high density	0.214	0.239	***0.469***	**0.531**	**0.513**	***0.393***	***0.406***
Urban combined	0.078	0.091	*0.358*	**0.432**	*0.353*	**0.390**	0.275
Percent impervious surface	0.037	0.003	*0.319*	***0.423***	***0.415***	***0.427***	0.219

Boxes with bold coefficients represent $p<0.01$, boxes with bold italicized coefficients represent $p<0.05$ and boxes with italicized coefficients represent $p<0.10$.
[a]Data log transformed.
[b]Spearman rank correlation.

Table 5 – Pearson product moment correlation coefficients of comparisons between the different land cover categories and the sediment quality variables considered separately for tidal creeks (T) and open water (O)

Land cover category	Silt-clay		TOC		ERM-Q		PAHs		PCBs		Pesticides		Metals	
	T[a]	O[a]	T[a]	O[a]	T[a]	O[b]	T[a]	O	T[c]	O[a]	T[c]	O[c]	T[a]	O[a]
Non-urban														
Scrub/shrub and forested wetlands	0.26	0.16	0.30	−0.11	−0.06	0.03	−0.01	−0.26	−0.14	0.04	−0.27	−0.09	−0.01	0.00
Bare land	−0.33	−0.32	***−0.57***	−0.27	***−0.48***	0.32	***−0.54***	−0.30	*−0.40*	−0.24	***−0.53***	−0.26	*−0.40*	−0.36
Grassland/pasture and scrub/shrub	−0.18	−0.36	−0.35	−0.29	***−0.53***	0.25	***−0.50***	−0.27	−0.25	−0.29	−0.30	−0.24	***−0.52***	−0.26
Deciduous and mixed forest	0.13	−0.26	0.10	*−0.38*	−0.34	0.33	−0.19	−0.36	−0.28	−0.23	−0.27	−0.44	−0.36	*−0.41*
Evergreen forest	0.28	−0.18	0.21	−0.15	***−0.53***	0.26	***−0.56***	**−0.44**	−0.17	−0.25	*−0.40*	−0.32	−0.45	−0.34
Cutlivated land	0.19	−0.27	0.18	−0.14	−0.18	0.25	−0.26	−0.26	0.03	−0.07	−0.08	−0.34	−0.23	−0.26
Urban														
Urban low density	−0.24	0.04	−0.09	0.12	*0.43*	−0.16	*0.42*	*0.38*	0.08	0.11	*0.45*	0.30	*0.39*	0.18
Urban high density	−0.14	*0.38*	−0.11	***0.44***	**0.62**	***−0.49***	**0.60**	**0.64**	0.18	*0.42*	***0.49***	*0.43*	***0.55***	**0.62**
Urban combined	−0.22	0.19	−0.11	0.26	***0.51***	−0.31	***0.49***	***0.51***	0.01	0.25	***0.46***	*0.39*	***0.46***	***0.38***
Percent impervious surface	*−0.48*	0.22	−0.27	0.27	***0.51***	−0.30	***0.55***	***0.51***	0.30	0.29	***0.56***	0.35	*0.40*	***0.39***

Boxes with bold coefficients represent $p<0.01$, boxes with bold italicized coefficients represent $p<0.05$ and boxes with italicized coefficients represent $p<0.10$. Note that ERM-Q values used for the open water analysis were inversely transformed. Therefore, negative values represent a positive correlation and visa versa.
[a]Data log transformed.
[b]Data inverse transformed
[c]Spearman rank correlation.

resource use and spatial extent of the problem. Approximately 62% of the stations sampled in estuaries with >50% urban cover had more than 43 colonies/100 mL whereas only about 17% of the stations in watersheds with <30% urban/suburban cover exceeded this threshold (Fig. 5).

Among the nutrient variables, only TKN, the predominant form of nitrogen in South Carolina estuaries, and TOC showed significant negative correlations with one or more of the non-urban land cover categories (Tables 6 and 7). Few nutrients showed significant correlations with the urban land cover categories (Table 6). When tidal creek and open water data were considered separately, only NO_2–NO_3 and total phosphorus showed a significant negative correlation with one or more of the urban land cover categories (Table 7).

4. Discussion

Based on the analyses reported here, estuarine water and sediment quality reflect urbanization of coastal watersheds at large spatial scales in the southeastern United States. Similar relationships, particularly between sediment contaminant levels and upland land use patterns, have been identified in other parts of the US (Comeleo et al., 1996; Dauer et al., 2000; Paul et al., 2002), but their applicability to the southeast was questionable due to differences in topography, tidal ranges and hydrography. While specific, small-scale estuarine responses to land use have been widely documented, as described in the following sections, emerging evidence from

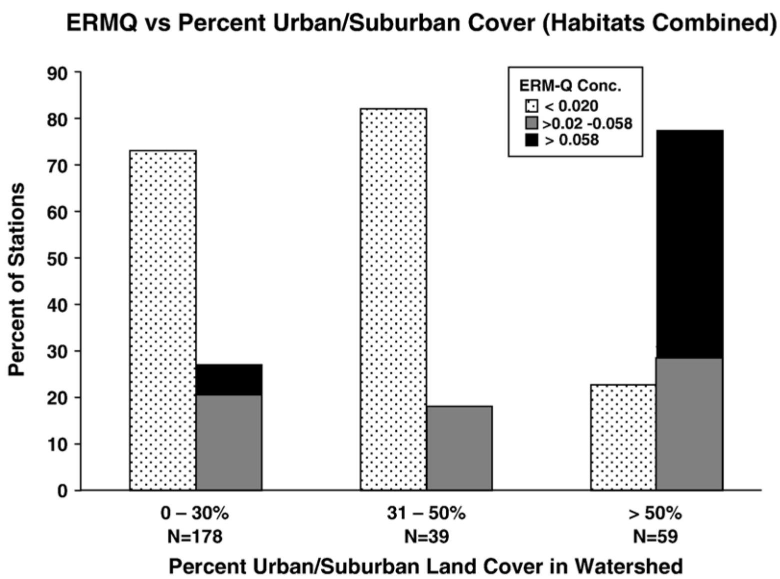

Fig. 4 – Percentage of stations with elevated ERM-Q contaminant concentrations in watersheds with varying amount of urban/suburban (urban combined) land cover. N represents the total number of stations in each group of watersheds.

Table 6 – Pearson product moment correlation coefficients of comparisons between the different land cover categories and the water quality variables using all stations (tidal creek and open water) combined

Land cover category	NO_2–NO_3	TKN[a]	Phos	TOC[a]	Chlor-a	Fecals[a]
Non-urban						
Scrub/shrub and forested wetlands	−0.002	***−0.330***	−0.169	−0.214	−0.043	**−0.393**
Bare land	−0.168	***−0.391***	−0.107	***−0.391***	−0.271	−0.195
Grassland/pasture and scrub/shrub	0.081	−0.054	−0.132	−0.076	−0.250	*−0.318*
Deciduous and mixed forest	0.042	***−0.324***	0.063	−0.119	−0.123	***−0.388***
Evergreen forest	0.242	−0.058	−0.192	0.064	0.179	−0.304
Cutlivated land	0.123	−0.200	0.019	−0.298	−0.141	−0.253
Urban						
Urban low density	−0.243	0.113	0.121	0.124	−0.069	***0.396***
Urban high density	−0.002	0.303	0.102	0.093	−0.059	***0.459***
Urban combined	−0.180	0.190	0.132	0.114	−0.053	***0.435***
Percent impervious surface	−0.055	0.225	0.170	0.106	−0.047	**0.476**

Boxes with bold coefficients represent $p<0.01$, boxes with bold italicized coefficients represent $p<0.05$ and boxes with italicized coefficients represent $p<0.10$.
[a]Data log transformed.

this and other studies indicates these small-scale responses do not attenuate to the point of non-significance, and in fact remain quite strong at larger spatial scales.

4.1. Sediment quality

Measures of sediment quality provided the strongest indicators of habitat disturbance due to urbanization in the coastal watersheds of South Carolina. The principal components analysis revealed a strong urbanization gradient in the environmental data matrix that was primarily related to the sediment contaminant measures (Fig. 3). This relationship is further supported by the significant positive correlations noted between the concentrations of ERM-Q and the contaminant subcategories (PAHs, PCBs, pesticides, and to a much lesser extent metals) and several of the urban/suburban land cover categories (Tables 4 and 5). These relationships, combined with the much higher percentage of stations having elevated ERM-Q concentrations in urbanized estuaries versus non-urbanized estuaries (Fig. 4), provide strong evidence that urbanization of coastal watersheds in South Carolina results in degradation of sediment quality.

Comeleo et al. (1996) noted that the influence of watershed stressors on sediment contaminant levels appeared to be greatest when sources were located within 10 km of the sampling station. Our study confirms that proximity to a source may be important with respect to overall contaminant burdens, since the relationships between overall contaminant levels (as measured by ERM-Q) and the urban land cover categories were much stronger in the tidal creek than in the open water data set (Table 5). This also tended to be the case for pesticides, but not PAHs, PCBs, or metals. However, both PAHs and metals were significantly and positively correlated with low-density urban cover in tidal creeks, whereas, open water sites showed no

Table 7 – Pearson product moment correlation coefficients of comparisons between the different land cover categories and the water quality variables considered separately for tidal creeks (T) and open water (O)

Land cover category	NO_2-NO_3		TKN		Phos		TOC		Chlorophyll-a		Fecals	
	T	O	T	O[a]	T	O	T	O	T[a]	O	T[a]	O[a]
Non-urban												
Scrub/shrub and forested wetlands	0.26	−0.11	−0.30	−0.19	0.09	−0.07	−0.10	−0.20	−0.38	0.061	**−0.45**	**−0.37**
Bare land	−0.45	−0.26	−0.46	−0.22	−0.14	0.04	−0.32	−0.20	−0.10	−0.08	0.11	−0.05
Grassland/pasture and scrub/shrub	−0.07	0.11	−0.41	−0.01	−0.01	−0.20	−0.15	−0.03	0.04	−0.13	−0.32	−0.22
Deciduous and mixed forest	*0.50*	−0.07	−0.32	−0.36	0.29	−0.07	0.02	−0.29	−0.01	−0.08	*−0.41*	**−0.61**
Evergreen forest	*0.52*	0.20	−0.03	−0.09	0.33	0.14	0.03	0.15	−0.07	0.59	−0.11	**−0.39**
Cutlivated land	0.09	−0.07	0.03	−0.28	−0.18	0.11	−0.30	**−0.47**	0.05	−0.25	0.13	*−0.32*
Urban												
Urban low density	*−0.53*	−0.10	0.02	0.15	−0.27	−0.07	0.19	0.07	0.27	−0.34	0.17	**0.49**
Urban high density	−0.41	0.13	0.27	0.34	*−0.46*	−0.11	−0.02	0.06	0.15	−0.40	0.36	**0.54**
Urban combined	*−0.52*	−0.04	0.12	0.23	−0.37	−0.08	0.11	0.06	0.25	−0.38	0.23	**0.53**
Percent impervious surface	−0.46	0.06	0.19	0.15	−0.26	−0.15	0.14	0.00	0.23	−0.33	*0.40*	**0.50**

Boxes with bold coefficients represent $p<0.01$, boxes with bold italicized coefficients represent $p<0.05$ and boxes with italicized coefficients represent $p<0.10$.
[a]Data log transformed.

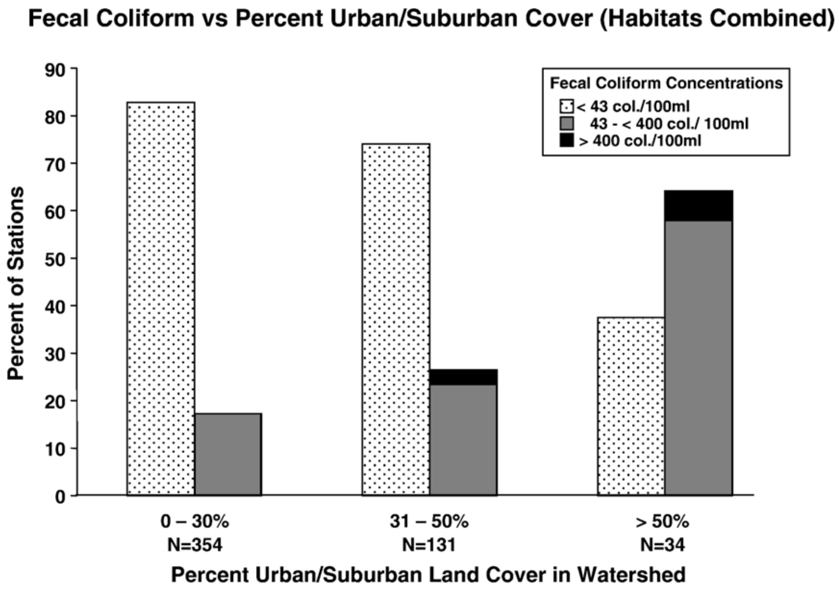

Fig. 5 – Percentage of stations with elevated fecal coliform bacteria concentrations in watersheds with 0–30, 31–50, and >50 percentage of urban/suburban (urban combined) land cover. *N* represents the total number of stations in each group of watersheds.

significant relationships for these contaminant classes. Tidal creeks represent the first point of entry for much of the land runoff in South Carolina and would be expected to show evidence of degradation before sites located in more distant and larger water bodies (Holland et al., 2004).

Ngabe et al. (2000) investigated the probable sources of PAHs in storm water runoff and estuarine waters close to shore and concluded that the PAH profiles were more similar to those associated with atmospheric deposition of combustion products than from other sources, such as crankcase oils. Van Dolah et al. (2005) also evaluated PAH concentrations in estuarine sediments in marshes, mud flats and tidal creeks adjacent to roads having different usage levels and concluded that the PAH concentrations attenuated to near background levels within the first 50 m from the road berm. Sanger et al. (1999b) observed significantly higher concentrations of both PAHs and PCBs in tidal creeks draining industrial/urban watersheds compared with creeks in suburban and forested watersheds, which suggests that these compounds do enter creek systems in highly urbanized, industrial areas.

While total PAH concentrations tended to be strongly associated with the urbanization gradient in South Carolina's coastal zone, interpretation of this relationship is not entirely straightforward. Principal component analysis identified a cluster of non-urbanized watersheds (all with <10% combined urban cover) with sediment characteristics and contaminant levels similar to very highly urbanized watersheds (those with >50% urban cover). Of the various parameters used to describe these non-urbanized watersheds, total PAH levels were particularly high, primarily due to the hydrocarbon perylene (up to 99% of the total at some stations). Conversely, perylene comprised a relatively small portion of the hydrocarbons present in any of the highly urbanized watersheds. Perylene is generally believed to represent a natural product of organic matter decomposition and that, in estuaries, reaches greatest abundance in highly productive waters (Venkatesan, 1988). *A-posteriori* examination of perylene concentration showed this hydrocarbon to be highly correlated with sediment TOC ($r=0.884$) and only weakly correlated with most of the other hydrocarbons examined in this study ($r=0.271$–0.538). Because most of the other hydrocarbons with known anthropogenic sources were strongly correlated with each other ($r>0.9$ in most cases) and only moderately correlated with sediment TOC ($r=0.259$ to 0.603), this suggests a completely different source for perylene as compared to the other measured hydrocarbons in South Carolina's coastal watersheds. In fact, when total PAH was recalculated to exclude perylene, the HUCs falling within cluster III in the PC plot moved closer to the other non-urbanized HUCs and total PAH became more strongly correlated with the various urban land cover categories (data not shown). This indicates that the naturally occurring hydrocarbon perylene can have a strong influence on total PAH concentrations in estuarine sediments and should be excluded from analyses examining anthropogenic impacts of aggregated PAH measures.

Since contaminant concentrations are generally highly correlated with the percentage of fine-grained material (silt/clay) or TOC in the sediments, it is interesting to note that neither of these sediment variables were significantly correlated with the urban/suburban land cover categories when all sites were considered collectively. For the open water data set, only the high urban density category was significantly positively correlated with these variables, and in the creek data set, only silt/clay was significantly and negatively correlated with the percent impervious surface. The latter finding was also observed by Holland et al. (2004) in headwater tidal creeks. Sanger et al. (1999b) noted that clay and TOC content of sediments in tidal creeks were strongly correlated with organic contaminants but more strongly correlated with metals. We generally found very strong correlations between the various contaminant categories and both silt/clay content and TOC (generally $p < 0.001$), so it is unclear why these variables were not strongly correlated with the land use categories. However, this does suggest that silt/clay and TOC are not driving relationships between contaminant concentrations and distributions versus the amount of watershed urbanization.

The relationships between the different urban land cover categories and the contaminant measures indicated that the intensity/type of urban/suburban land cover is important. ERM-Q and most of the contaminant subcategories, as well as silt/clay and TOC, had the strongest and most significant correlations with the high-density urban land cover (Tables 4 and 5). These measures tended to be less strongly correlated with urban combined land cover and the percentage of impervious surface cover. In comparison, low-density urban land cover, which corresponds most closely with suburban land cover, generally showed either a relatively weak significant correlation, or no correlation with ERM-Q or the contaminant subcomponents. Sanger et al. (1999a,b) also noted that, in tidal creek sediments, suburban watersheds had significantly lower concentrations of most organic compounds and many metals as compared to the urban/industrial watersheds.

Contaminant levels characterizing South Carolina's coastal watersheds likely originate from human activities within coastal watersheds rather than from more inland sources. There are numerous non-local sources of contaminants in estuarine and coastal habitats including atmospheric deposition (Ngabe et al., 2000) and point-source discharges from either local industrial effluents or river/base flows into the estuaries (Paul et al., 2002; Hwang and Foster, 2006). While we do not have data on contaminant loadings from inland river sources, very few of the coastal watersheds we considered have significant, if any, river discharge from inland sources. Thus, the only other sources most likely to influence contaminant levels are atmospheric deposition and industrial outfalls. Only industrial outfalls are easily regulated. Certainly the relative inputs from non-point source runoff, point source discharge into estuaries and atmospheric deposition deserve further attention.

4.2. *Water quality*

In general, water quality parameters did not respond as strongly as the sediment quality parameters to urbanization. Nutrients and fecal coliform bacteria did not contribute much to the variability observed among the HUCs based on the principal components analysis (Table 2) and this was generally supported by the correlation analyses of the individual water quality variables with the land cover categories (Tables 6 and 7). Among the water quality variables considered, fecal coliform bacteria responded more strongly to the various urban/suburban land cover categories than the waterborne nutrients. Fecal coliform bacteria concentrations were generally not significantly correlated with land cover categories when only the tidal creek data were considered, but they were significantly and positively correlated to most of the urban/suburban land cover categories when only the open water data set was considered. The lack of more significant relationships in the tidal creek data set was surprising since these habitats are the closest to sources of either human or wildlife bacterial runoff. Mallin et al. (2000) and Holland et al. (2004) have documented strong relationships between the concentrations of fecal coliform bacteria and the amount of urbanization, with particularly significant relationships noted between fecal bacterial concentrations and percent impervious cover. Felber (2007) examined a large number of creek sites of varying size in South Carolina and found strong relationships between fecal coliform bacteria concentrations and the amount of urbanization in the surrounding upland area. He also observed a significant decrease in fecal coliform bacterial concentrations as creek size increased. Van Dolah et al. (2003) also observed significantly higher concentrations of fecal coliform bacteria in tidal creeks than in larger open water bodies in South Carolina. It is therefore unclear why we did not see a more significant relationship between bacterial concentrations and urban land cover categories in the tidal creek analyses.

Analyses of fecal coliform data using the combined data set suggest that upland urbanization can negatively impact the safe consumption of shellfish resources. The much higher incidence of sites having elevated fecal bacteria concentrations in the watersheds with a high versus low percentage of urban cover (Fig. 5) indicates that these watersheds are likely to support little if any areas suitable for oyster harvesting in this state.

The lack of significant relationships in most of the other water quality variables may be due to the more limited number of stations sampled for these variables compared to the number of stations that had data for fecal coliform bacteria and the sediment contaminant variables. Additionally, the high tidal flushing of South Carolina estuaries tends to result in lower nutrient concentrations than less flushed areas (Lewitus et al., 2003, Brock, 2006; Van Dolah et al., 2006) and most of South Carolina's estuarine habitat is not considered to be nutrient enriched (Van Dolah et al., 2002, 2004a, 2006). This is also supported by the lack of any significant correlations between chlorophyll-a concentrations and the land cover categories.

5. Conclusions

The effects of urbanization of coastal uplands in the southeastern United States is detectable in estuarine environmental quality at large spatial scales (14-digit HUC) with respect to sediment contaminants and fecal coliform bacterial concentrations, but generally not with measures of nutrient variables. All of the sediment contaminant classes considered (PAHs, PCBs, pesticides, metals) increased significantly in concentration with increasing urban land cover, particularly high-density urban cover. These findings indicate that upland urbanization can result in increased risk of biological degradation and reduced safe human use of South Carolina's coastal resources.

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REFERENCES

Arnold CL, Gibbons CJ. Impervious surface coverage. J Am Plan Assoc 1996;62:243–58.

Bricker SB, Clement CG, Pirhalla DE, Orlando SP, Farrow DRG. National estuarine eutrophication assessment: effects of nutrient enrichment in the nation's estuaries. National Oceanic and Atmospheric Administration, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Maryland: Silver Spring; 1999. 71 pp.

Brock, LM. Water quality, nutrient dynamics, phytoplankton ecology and land uses within defined watersheds surrounding six detention ponds on Kiawah Island, South Carolina. Masters Thesis, College of Charleston, Charleston, SC; 2006.

Comeleo RL, Paul JF, Augus PV, Copeland J, Baker C, Hale SS, et al. Relationships between watershed stressors and sediment contamination in the Chesapeake Bay estuaries. Landsc Ecol 1996;11:307–19.

Dauer DM, Ranasinghe JA, Weisberg SB. Relationships between benthic community condition, water quality, sediment quality, nutrient loads, and land use patterns in Chesapeake Bay. Estuaries 2000;23:80–96.

Felber, J. Variability of fecal coliform concentration with regard to creek order, tide stage, rainfall, and land use patterns. Thesis submitted to Master of Science in Environmental Studies. College of Charleston; 2007. 90p.

Fulton MH, Scott GI, Fortner A, Bidleman TF, Ngabe B. The effects of urbanization on small high salinity estuaries of the southeastern United States. Arch Environ Contam Toxicol 1993;25:476–84.

Holland AF, Sanger DM, Gawle CP, Lerberg SB, Santiago MS, Riekerk GHM, et al. Linkages between tidal creek ecosystems and the landscape and demographic attributes of their watersheds. J Exp Mar Biol Ecol 2004;298:151–78.

Hwang H, Foster GD. Characterization of polycyclic aromatic hydrocarbons in urban storm water runoff flowing into the tidal Anacostia River, Washington, DC, USA. Environ Pollut 2006;140:416–26.

Hyland JL, Herrlinger TJ, Snoots TR, Ringwood AH, Van Dolah RF, Hackney CT, et al. Environmental quality of estuaries of the Carolinian Province: 1994. Annual statistical summary for the 1994 EMAP-Estuaries Demonstration Project in the Carolinian Province. NOAA Technical Memorandum NOS ORCA 97. NOAA/NOS, Office of Ocean Resources Conservation and Assessment. MD: Silver Spring; 1996. p. 102.

Hyland JL, Balthis L, Hackney CT, McRae G, Ringwood AH, Snoots TR, et al. Environmental quality of estuaries of the Carolinian Province: 1995. Annual statistical summary for the 1995 EMAP Estuaries Demonstration Project in the Carolinian Province. NOAA Technical Memorandum NOS ORCA 123 NOAA/NOS, Office of Ocean Resources Conservation and Assessment. M.D: Silver Spring; 1998. p. 143.

Hyland JL, Van Dolah RF, Snoots TR. Predicting stress in benthic communities of southeastern U.S. estuaries in relation to chemical contamination of sediments. Environ Toxicol Chem 1999;18(11):2557–64.

International Marine. Tide tables 1996. High and low water predictions. East Coast of North and South America, Including Greenland. Camden, ME: International Marine; 1995.

Kelsey H, Porter DE, Scott G, Neet M, White D. Using geographic information systems and regression analysis to evaluate relationships between land use and fecal coliform bacterial pollution. J Exp Mar Biol Ecol 2004;298:197–209.

Lewitus AJ, Schmidt LB, Mason LJ, Kempton JW, Wilde SB, Wolny JL, et al. Harmful algal blooms in South Carolina residential and golf course ponds. Popul Environ 2003;24:387–413.

Long ER, MacDonald DD, Smith SL, Calder FD. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environ Manage 1995;19:81–97.

Long ER, Scott GI, Kucklick J, Fulton M, Thompson B, Carr RS, et al. Final report. Magnitude and extent of sediment toxicity in selected estuaries of South Carolina and Georgia. NOAA technical memorandum NOS ORCA: 178 p. Technical summary report 57; 1997.

Mallin MA, Williams KE, Esham EC, Lowe RP. Effect of human development on bacteriological water quality in coastal watersheds. Ecol Appl 2000;10:1047–56.

Nelson KA, Scott GI, Rust PF. A multivariable approach for evaluating major impacts on water quality in Murrells and North Inlets, South Carolina. J Shellfish Res 2005;24:1241–51.

Ngabe B, Bidleman TF, Scott GI. Polycyclic aromatic hydrocarbons in storm runoff from urban and coastal South Carolina. Sci Total Environ 2000;255:1–9.

Paul JF, Comeleo RL, Copeland J. Landscape and watershed processes: landscape metrics and estuarine sediment contamination in the mid-Atlantic and southern New England regions. J Environ Qual 2002;31:836–45.

Ringwood AH, Van Dolah RF, Holland AF, DeLorenzo ME, Keppler C, Maier P, et al. Year two demonstration project studies conducted in the Carolinian Province by Marine Resources Research Institute: results and summaries. Final report submitted to the NOAA/EMAP Carolinian Province Office, Charleston, SC; 1997. p. 154. plus appendices.

Sanger DM, Holland AF, Scott GI. Tidal creek and salt marsh sediments in South Carolina Coastal Estuaries. I. Distribution of trace metals. Arch Environ Contam Toxicol 1999a;37:445–57.

Sanger DM, Holland AF, Scott GI. Tidal creek and salt marsh sediments in South Carolina Coastal estuaries. II. Distribution of organic contaminants. Arch Environ Contam Toxicol 1999b;37:458–71.

Schueler TR. The importance of imperviousness. Watershed Prot Tech 1994;1:100–11.

Schueler TR, Holland HK. The practice of watershed protection. Ellicott City, MD: Center for Watershed Protection; 2000.

South Carolina Budget and Control Board. South Carolina Statistical Abstract 2005. Prepared by the Office of Research and Statistics 1919 Blanding St. Columbia, SC 29201; 2005. Available online at www.ors2.state.sc.us/abstract/index.asp.

South Carolina Department of Health and Environmental Control. Laboratory procedures manual for environmental microbiology. Columbia, S.C.: Bureau of Environmental Services; 1998.

South Carolina Department of Health and Environmental Control. Environmental investigations standard operating procedures and quality assurance manual. Columbia, SC: Office of Environmental Quality Control; 2001.

South Carolina Department of Health and Environmental Control. Water classifications and standards (Regulation 61–68) and classified waters (Regulation 61–69) for the State of South Carolina. Columbia, S.C.: Office of Environmental Quality Control; 2004.

South Carolina Department of Health and Environmental Control. Procedures and quality control manual for chemistry laboratories. Columbia, S.C.: Bureau of Environmental Services; 2005. South Carolina Department of Health and Environmental Control.

U.S. Environmental Protection Agency. National coastal condition report II; 2004. EPA-620-R-03-002. 286 p.

Van Dolah RF, Chestnut DE, Scott GI. A baseline assessment of environmental and biological conditions in Broad Creek and the Okatee River, Beaufort County, South Carolina. Final Report to Beaufort County Council; 2000. p. 281.

Van Dolah, RF, Jutte, PC, Riekerk, GHM, Levisen, MV, Zimmernman, LE, Jones, AD, et al. The condition of South Carolina's estuarine and coastal habitats during 1999–2000: technical report. Charleston, SC: South Carolina Marine Resources Division. Technical Report No. 90; 2002. 132 p. plus appendices.

Van Dolah RF, Chestnut DE, Jones JD, Jutte PC, Riekerk G, Levisen M, et al. The importance of considering spatial attributes in evaluating estuarine habitat condition: the South Carolina experience. Environ Monit Assess 2003;81:85–95.

Van Dolah, RF, Jutte, PC, Riekerk, GHM, Levisen, MV, Zimmernman, LE, Jones, JD et al. The condition of South Carolina's estuarine and coastal habitats during 2001–2002: technical report. Charleston, SC: South Carolina Marine Resources Division. Technical Report No. 100. 70 p.

Van Dolah, RF, Sanger, DM, Filipowicz, AB, editors. A baseline assessment of environmental and biological condition in the May River, Beaufort County, South Carolina. A final report submitted to the Town of Bluffton, SC. Produced by the South Carolina Department of Natural Resources, the United States Geological Survey, and the National Oceanic and Atmospheric Administration, National Ocean Service : 2004b. 226 p.

Van Dolah RF, Riekerk GHM, Levisen MV, Scott GI, Fulton MH, Bearden D, et al. An evaluation of polycyclic aromatic hydrocarbon (PAH) runoff from highways into estuarine wetlands of South Carolina. Arch Environ Contam Toxicol 2005;49:362–70.

Van Dolah, RF, Bergquist, DC, Riekerk, GHM, Levisen, MV, Crowe, SE, Wilde, SB, et al. The condition of South Carolina's estuarine and coastal habitats during 2003–2004: technical report. Charleston, SC: South Carolina Marine Resources Division. Technical Report No 2006. 101 70 p.

Venkatesan MI. Occurrence and possible sources of perylene in marine sediments: a review. Mar Chem 1988;25:1–27.

Vernberg FJ, Vernberg WB, Blood E, Fortner A, Fulton M, McKellar H, et al. Impact of urbanization on high-salinity estuaries in the southeastern United States. Neth J Sea Res 1992;30:239–48.

Vernberg WB, Scott GI, Strozier SH, Bemiss J, Daugomah JW. The effects of urbanization on human and ecosystem health. In: Vernberg FJ, Vernberg WB, Siewicki T, editors. Sustainable development in the southeastern coastal zone. Columbia, SC: University of South Carolina Press; 1996. p. 221–39.

Zinn JA. Coastal demographics and development patterns; 1997. Congressional Research Service Report 97-588 ENR.